Diving Deeper: Exploring the Feasibility of Lowering Cassini's Final Orbits

Erick J. Sturm II
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109
818-393-6449
Erick.J.Sturm@jpl.nasa.gov

Abstract—**During the final five orbits of Cassini's mission, the spacecraft will get closer to Saturn than it has ever been. These five orbits were designed to be as deep in the atmosphere as Cassini could safely fly; however, recent occultation data of Saturn's atmosphere suggest that it is contracting. Given this contraction, the primary concern during these orbits has shifted from spacecraft health and safety to loss of science value. This paper explores a scenario for modifying the Cassini spacecraft's trajectory, during these final orbits, such that it dips deeper into Saturn's atmosphere.**

This scenario describes the method for in-situ detection of Saturn's atmospheric state, the locations and sizes of maneuvers that would reduce the final periapsis altitudes, the effects of such maneuvers on the remaining trajectory, and the risks involved.

The result is that a periapsis-lowering, "pop-down" maneuver is feasible during Cassini's final orbits. Risk to the spacecraft is minimized by using the attitude control thrusters as density detectors during the first three atmospheric transits of the final five orbits. Should these transits reveal sufficiently low density and should sufficient propellant remain, then the Cassini project will consider performing the maneuver.

TABLE OF CONTENTS

1. INTRODUCTION

In April 2017, Cassini will begin its Grand Finale, a series of 22½ orbits that will take the spacecraft between Saturn and its rings. During the final five orbits, Cassini will fly low enough that it will take in-situ measurements of Saturn's thermosphere. As such, these final orbits provide a unique opportunity to obtain some of the most valuable science data of the entire Cassini mission. However, recent occultations of Saturn's atmosphere suggest that it is contracting, which could mean that the spacecraft will no longer fly through atmosphere of sufficient density to obtain high quality, in-situ measurements.

While significant work has been done to model the atmosphere, the focus has been on spacecraft health and safety, using the model to ensure that the nominal trajectory poses no threat to loss of attitude control due to aerodynamic torques [1]. With the contracting of Saturn's atmosphere, the focus has shifted to using the model to see how low the spacecraft could go before the atmosphere poses a significant risk. Modifying the nominal trajectory to fly lower in the atmosphere would require an orbital trim maneuver (OTM). In order to reduce risk to the spacecraft, the decision to execute such a "pop-down" maneuver would be made only after in-situ detection of a low-density atmosphere; however, performing a maneuver would require all subsequent spacecraft activities to be tolerant of the timing differences between the nominal and lowered trajectories. In addition, the analysis to determine the state of the atmosphere, as well as the design of the maneuver, would have to be done relatively quickly given the orbital period of less than seven days.

This paper explores the feasibility of a scenario in which a pop-down maneuver is performed during the final five orbits in order to lower the atmospheric transit altitudes of subsequent periapsis passages. The scenario not only includes the locations and magnitudes of potential orbital trim maneuvers but also the method for detecting a low-density atmosphere during the early orbits of the final five. In addition, the scenario goes on to describe the consequences of performing such maneuvers in terms of the timing errors they introduce into the remaining trajectory. The scenario also lays out a reference timeline to ensure that there is in fact adequate time and DSN coverage to do all of the above. Lastly, the risk involved in performing the pop-down are considered.

Proximal Orbits

The proximal orbits, also known as Cassini's Grand Finale, are the final 22½ orbits of the Cassini Solstice Mission, which conclude with the spacecraft permanently entering Saturn's atmosphere. They get their name from their proximity to Saturn and its rings as their periapsis passages fly between the lower fringes of the D ring and the upper reaches of Saturn's atmosphere. Figure 1 shows Cassini's Grand Finale, which starts at apoapsis of Rev 271. After completing 22 full orbits (shown in blue), the spacecraft will make the journey from Titan to Saturn one last time (shown in orange). Finally, diving deep into Saturn's atmosphere on Rev 293, it will be destroyed.

While the Grand Finale consists of 22½ orbits, it is completed less than five months from its start. The short duration is due to the size of the orbits; with periapsis so close to Saturn and apoapsis only slightly outside of Titan's orbit, the period of each orbit is less than one week. Thus, the entire span of this scenario is about one month.

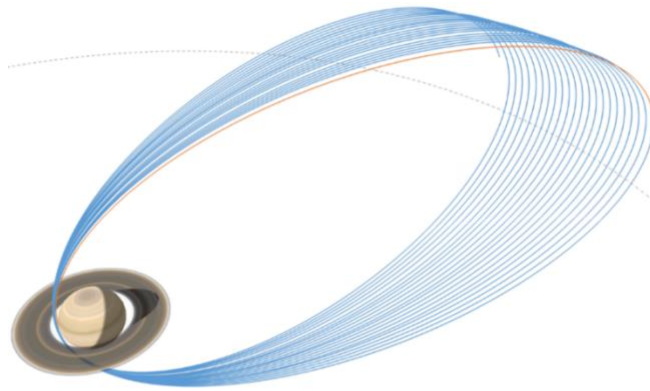


Figure 1. Cassini's Grand Finale with the 22 full proximal orbits in blue, the final half-orbit in orange, and Titan's orbit in gray.

The Final Five—While all the proximal orbits have periapsis passages between Saturn's atmosphere and rings, the exact altitudes of periapsis vary by over 2000 km. Distant, non-targeted Titan flybys out near the orbits' apoapses cause these differences. As shown in Figure 2, the altitudes of the final five orbits (revs 288-292) are the lowest in the Grand Finale by 1000 km. As such, these orbits provide the opportunity to obtain the best in-situ atmospheric measurements of the Grand Finale.

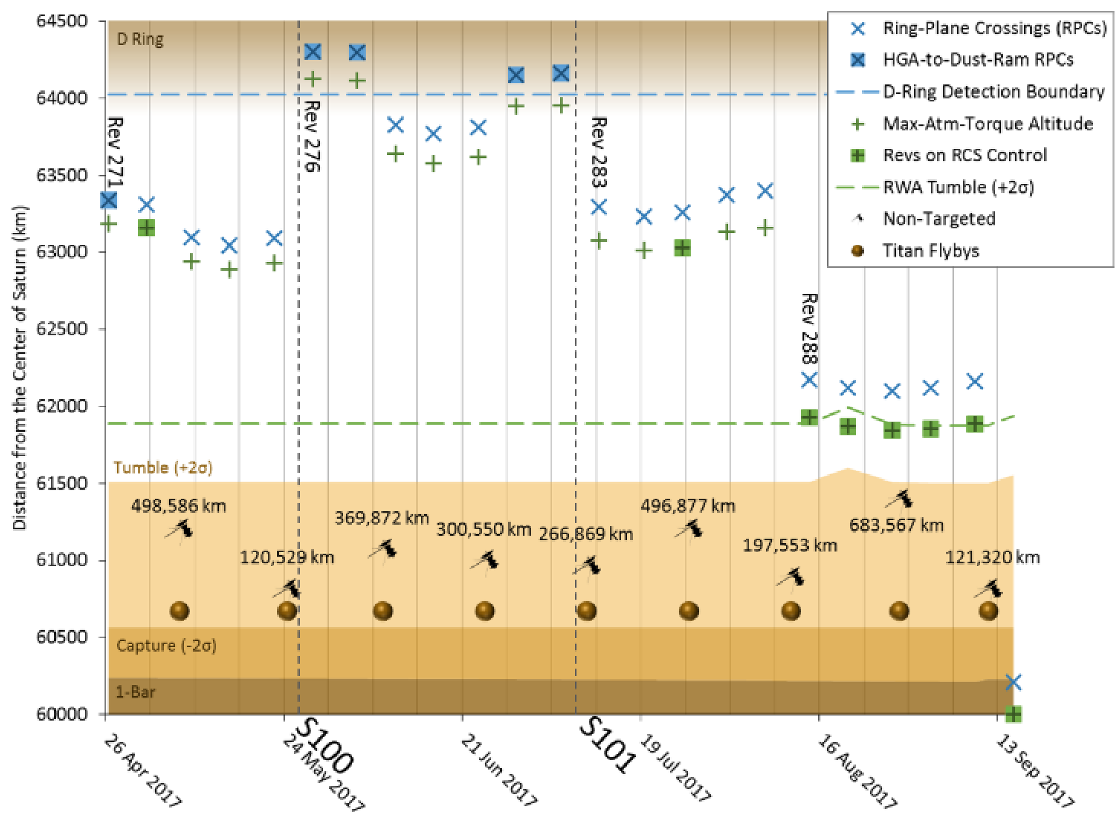


Figure 2. Variations in the altitudes of ring-plane crossings (blue) and points of maximum-atmospheric-torque (green) during the proximal orbits. The non-targeted Titan flyby distances that cause the variations are also shown (on a separate scale).

Zooming in on Figure 2 to show only the final five orbits, results in Figure 3, which shows that the final five orbits go progressively deeper into Saturn's atmosphere until Rev 290 and then start to climb back out again.

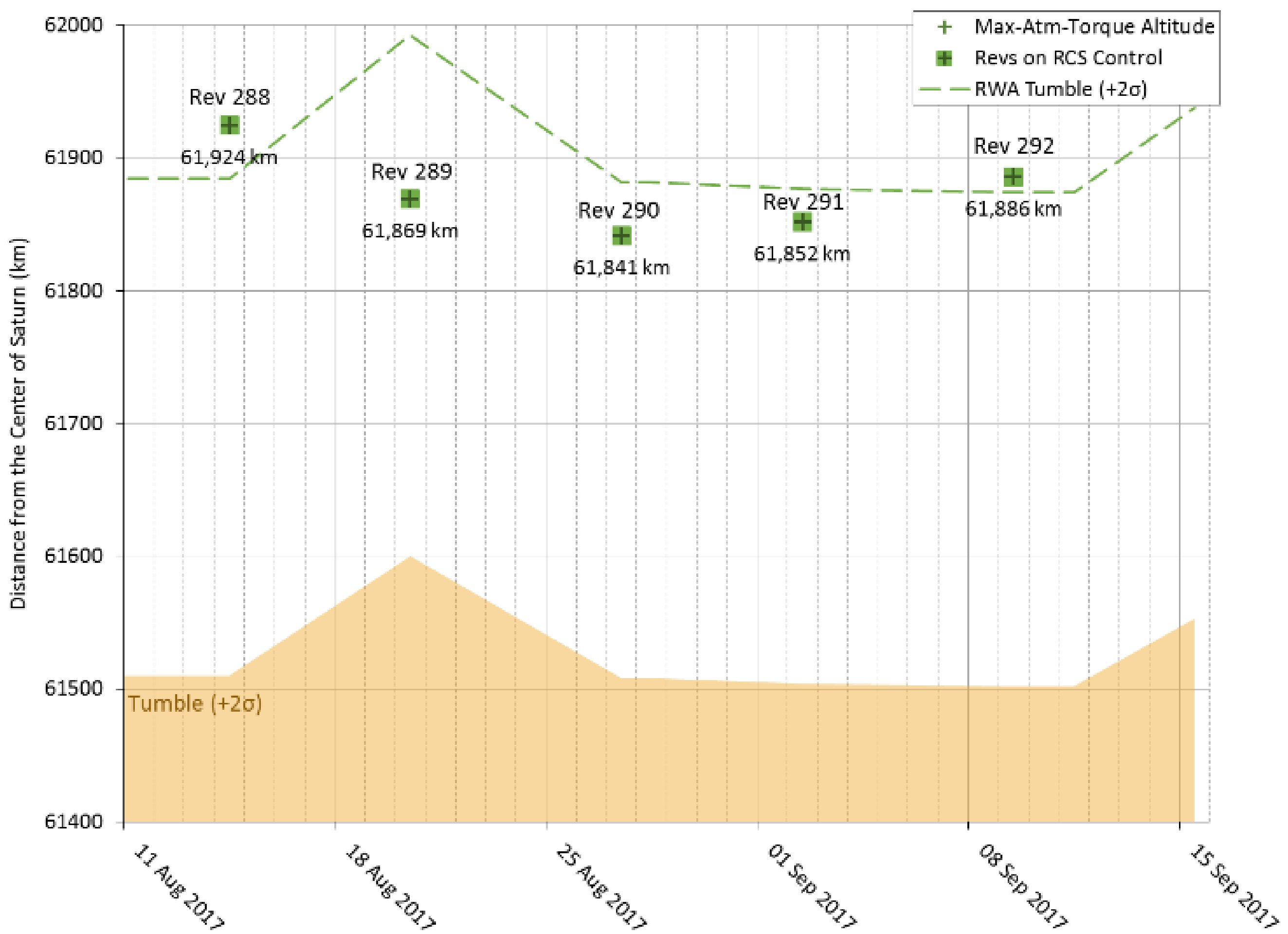


Figure 3. Maximum-atmospheric-torque altitudes of the final five proximal orbits.

Figure 3 also shows that there is about a 300-km margin between the spacecraft altitudes and the 2σ tumble boundary. Back when these orbits were designed, this margin was only tens-of-kilometers; however, recent occultation data suggest that Saturn's atmosphere is contracting and with it, the tumble altitude [2].

End of Mission—The last non-targeted Titan flyby, 292TI, is just before apoapsis of Rev 293 and sets up the final plunge of the spacecraft into Saturn. The last 14.5 hours of the mission will have continuous DSN coverage with the final 3.5 hours providing a near-real-time downlink. Figure 4 shows the geometry of the final orbit with key events labeled.

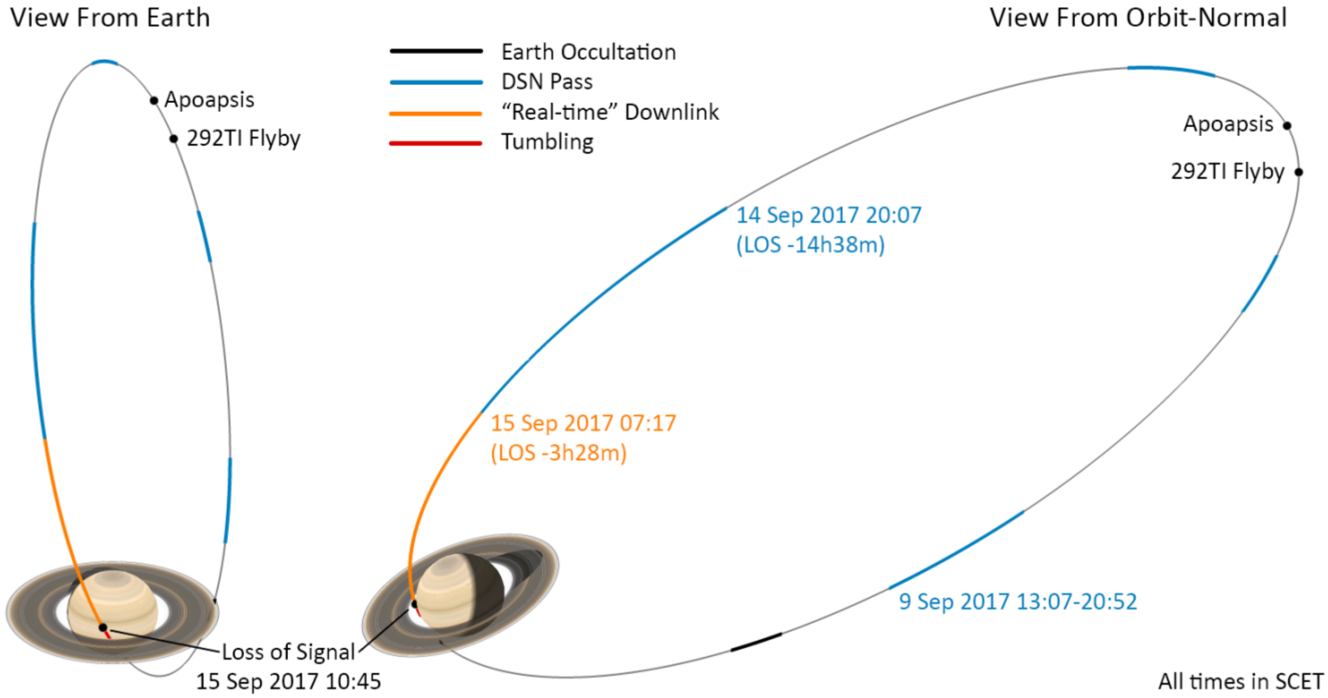


Figure 4: End-of-mission orbit geometry from Rev 292 periapsis to Saturn impact. On the left, is the view from Earth. On the right, is the view along the orbit normal. Times shown are in spacecraft event time (SCET).

The project is currently predicting loss of signal to occur on September 15, 2017 at 10:45 (SCET) [3].

Saturn Thermosphere Model

The Saturn thermosphere model is a two-dimensional model of density that varies with radius and latitude. D. Strobel and T. Koskinen developed the model through analysis of ultraviolet solar and stellar occultations of Saturn's atmosphere [2].

The model provides estimates for the atmospheric densities the spacecraft will fly through during the proximal orbits. When combined with the planned attitudes of the spacecraft, the Cassini flight-system-dynamics simulator (FSDS) can predict the peak RCS thruster duty-cycles required to fight the atmospheric torque. In addition, the model, the planned attitudes, and the maximum RCS thruster torque combine to define a spacecraft tumble boundary, the radius at which the density is sufficient to overwhelm the RCS thrusters and cause the spacecraft to lose control authority. This boundary is shown as the light yellow area in Figure 2 and Figure 3.

The model was originally developed using occultation data from 2009. While not fully known at the time, these data corresponded to an expanded state of Saturn's thermosphere. As a result, the tumble boundary was high and margin was low; the project was concerned with flying through too much atmosphere, not too little. More recent occultation data suggest that not only has the expansion of the atmosphere stopped but that a contraction has likely begun.

The current version of the model (dated July 2015) now includes two number densities: one for the 2015 state of the thermosphere and one for the predicted, 2017 state. The 2015 state is about two-thirds the density of the 2009 values. The predicted, 2017 state is half of that, about one-third the 2009 values. Now, spacecraft health and safety no longer seems to be at risk from the atmosphere, but the science teams are concerned the spacecraft may not be flying through enough atmosphere for instruments to adequately sample the density. More occultations are scheduled for late 2016 and early 2017, which will give a better indication of the state the atmosphere will be in during the proximal orbits. If necessary, the thermosphere model will be updated to account for those occultation data.

Cassini Spacecraft

The two key subsystems of the Cassini spacecraft for this scenario are the attitude and articulation control subsystem (AACS) and the propulsion module subsystem (PMS). The AACS will serve as a density detector during the atmospheric transits of the final five proximal orbits, while the PMS will perform the pop-down maneuver.

Attitude and Articulation Control—The AACS has two methods for maintaining control authority of the spacecraft: the reaction wheel assemblies (RWAs) and the reaction control system (RCS) thrusters of the PMS. The majority of the time, the spacecraft is on RWA control, occasionally switching to RCS control for momentum management. The spacecraft uses the RCS most often for high-speed turns and during low Titan flybys, to maintain control authority against the large torque exerted by Titan's atmosphere. Similarly, the spacecraft will be on RCS control during Saturn atmospheric transits in the proximal orbits.

The project will take advantage of the RCS in order to estimate the density of Saturn's thermosphere, as the percentage of time the thrusters fire (their duty-cycle) during a transit is directly proportional to the atmospheric torque, which is a function of density. Thruster duty-cycle has the additional advantage of being quick to calculate with a relatively low uncertainty of about ±1% (2σ).

Propulsion Module—The Cassini propulsion module subsystem is comprised of two separate propulsion systems: a bipropellant system with the main-engine assembly (MEA) and a monopropellant, reaction-control system (RCS) [4]. The locations of the main engines and RCS thruster pods are shown in Figure 5.

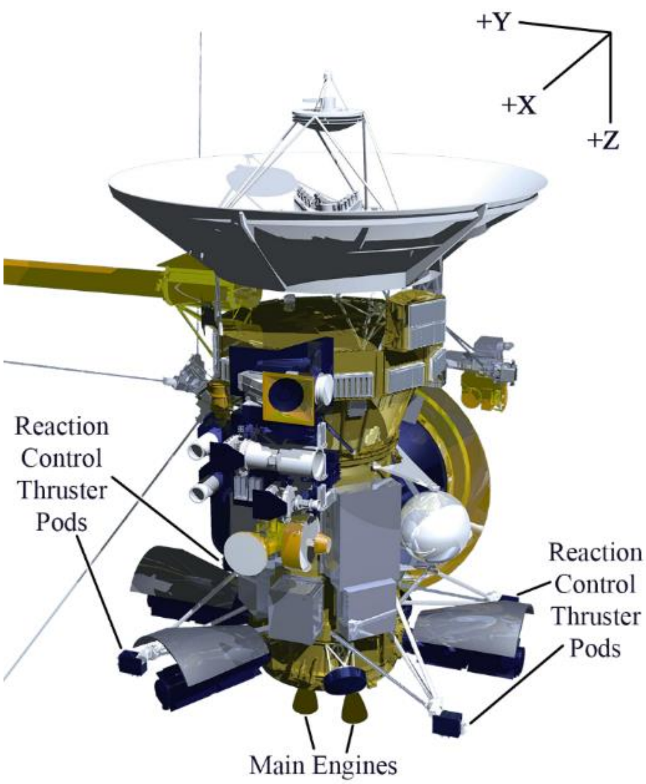


Figure 5: Cassini Spacecraft Thrusting Components

The Cassini spacecraft has two main engines and four RCS pods, each with four thrusters. Each RCS pod has two thrusters pointed along the +Z-axis and two thrusters pointed along either the +Y-axis or the –Y-axis depending on whether the pod is located on the +Y or –Y side of the X-Z plane. The thrusters are also separated into two branches, A and B, each with four +Z thrusters, two +Y thrusters, and two –Y thrusters. The spacecraft currently uses the B branch due to premature degradation of some of the +Z thrusters in the A branch. While there is no indication of any B branch thruster degradation at this time, should it occur before the end of mission, the spacecraft could operate in a mixed branch mode, using thrusters from both the A and B branches.

The bipropellant system uses nitrogen tetroxide (NTO) as its oxidizer and monomethylhydrazine (MMH) as its fuel. The spacecraft uses the MEA solely for orbital trim maneuvers greater than 250 mm/s. The spacecraft uses the RCS for small translational maneuvers, attitude control, and spacecraft momentum management. The spacecraft can also use the RCS for larger translational maneuvers, the maximum being approximately 4 m/s in a single burn executed during a standard nine-hour Deep Space Network pass.

Orbital Trim Maneuvers

An orbital trim maneuver (OTM) requires time for orbit determination, maneuver design, and execution windows (primary and back-up). A pop-down maneuver is most efficient when performed at apoapsis, which means the Navigation Team would have a little over three days to obtain tracking data, determine the orbit, and design the maneuver. The minimum duration required to perform the aforementioned tasks is shown in Table 1.

Table 1: Minimum durations for maneuver design.

Task	Minimum Duration
Obtain tracking data (two, daily, nine-hour passes)	33 hours
Orbit determination	3 hours
Maneuver design	3 hours
Navigation team review	1 hour
Total	**40 hours**

Including the time to obtain the tracking data, the Navigation Team requires at least 40 hours to finalize a maneuver.

Propellant Levels

The amount of propellant predicted to be remaining in the spacecraft during the proximal orbits is of vital importance to feasibility of this scenario, as without sufficient propellant the spacecraft could not perform a pop-down maneuver.

As of the completion of OTM-456 (2 Aug 2016), there is less than a 7% chance of depleting the bipropellant before the end of the mission. However, even with the assumption that the spacecraft depleted the bipropellant at the end of that OTM, there are about 25 m/s of margin between the ΔV required to fly the remaining mission and the ΔV that the monopropellant system alone can provide. Depending on how long the bipropellant lasts, the hydrazine margin could grow to be as large as 28 m/s by the time of this scenario. In addition, the bipropellant mean margin is predicted to be 20 m/s at end-of-mission. Moreover, the propellant usage predictor that generated these estimates has been shown to be accurate within 0.4 m/s over a three-year prediction period [5].

2. Pop-Down Scenario Overview

The pop-down scenario begins with the downlink of the RCS thruster firing data for the Rev 288 atmospheric transit; Rev 288 being the first orbit of the final five. The AACS team will use these data to calculate the peak duty-cycles of the RCS thrusters during the transit, which will then be compared to the predicted values. This will give the project an initial indication of the state of Saturn's atmosphere; however, no action will be taken until the process is repeated two more times during revs 289 and 290.

After the Rev 290 transit, if the peak duty-cycles are low, the project has two options: continue with the current trajectory or perform a pop-down maneuver near the Rev 291 apoapsis to lower the following periapsis altitudes. Such a maneuver would affect *all* subsequent periapsis altitudes not just the next one, unless an additional maneuver is performed to return to the reference trajectory. Thus, a pop-down maneuver performed at this time would lower the transits of revs 291 and 292.

Whether the above pop-down is performed or not, the project will have the same options available after the Rev 291 transit: either continue on the current trajectory or perform a pop-down, this time near the Rev 292 apoapsis.

Requirements and Objectives

The only requirement during this phase of the mission pertains to planetary protection, specifically proper disposal of the spacecraft, which the project will accomplish through permanent capture within Saturn's atmosphere. For this scenario, that requirement effectively means that any modifications to the spacecraft's flight path shall maintain a ballistic, Saturn-impacting trajectory. Furthermore, the location of Saturn impact shall have line-of-sight to Earth, such that loss-of-signal coincides with loss of attitude control and not an occultation from Saturn or its rings.

The sole objective of this scenario is to modify some portion of the spacecraft's trajectory during the final five proximal orbits such that it passes through the thickest atmosphere possible while still respecting spacecraft health-and-safety limits. In addition, the pop-down implementation should minimize the impact to the background sequence activities downstream of the maneuver.

Assumptions and Constraints

This scenario assumes the Cassini spacecraft to be operating nominally. The scenario also assumes sufficient propellant to perform not only the pop-down maneuver(s) but also the remaining planned spacecraft activities. An assumption is not made as to which type of propellant (hydrazine or bipropellant) must be used to perform the pop-down maneuver(s); however, bipropellant is considered the baseline option. Should a pop-down be performed with the RCS thrusters (hydrazine), the maximum ΔV of a single burn is constrained to no more than 4.0 m/s. Larger burns would require more time than is available in a single, 9-hour Deep Space Network pass to uplink the maneuver, turn to the burn attitude, perform the burn, turn back to Earth, and confirm the burn given the increased burn duration [6].

3. Atmospheric Density Detection

As discussed in the introduction, this scenario uses the AACS as a density detector. By analyzing the RCS thruster duty-cycles during the atmospheric transits and comparing them to the predicted values, the project can infer the density of the atmosphere. Each atmospheric transit will result in two, peak, duty-cycle estimates, one for the Y-thrusters and one for the Z-thrusters. The AACS team calculated the predicted peak Y and Z duty-cycles for the atmospheric transits of the final five orbits. In addition, the Mission Planning (MP) team did an uncertainty analysis to determine the likelihood of distinguishing differences between predicted and actual duty-cycles caused by the density of the atmosphere from those caused by other uncertainties. The sources of the other uncertainties that MP considered are navigation dispersions, spacecraft aerodynamics, mass properties, and RCS characteristics. The sources and their associated uncertainty values are shown in Table 2.

Table 2: Uncertainty sources of the duty-cycle uncertainty analysis

Source	Unc. (1σ)	Units
Duty-cycle Calculation	0.5%	---
Navigation		
Radius	6.9	km
Velocity	10	m/s
Spacecraft		
Drag Coefficient	0.033	---
Drag Area	0.117	m^2
Center of Press.		
CPx	0.011	m
CPy	0.204	m
CPz	0.080	m
Center of Mass		
CMx	0.003	m
CMy	0.007	m
CMz	0.019	m
RCS Thrust	0.010	N

The results of the uncertainty analysis are shown in Figure 6. The peak duty-cycles (Y and Z) for the final five orbits are shown with 2σ error bars from the sources identified above assuming a nominal atmosphere as predicted by the model, as well as 2σ-off-nominal atmospheres (high and low).

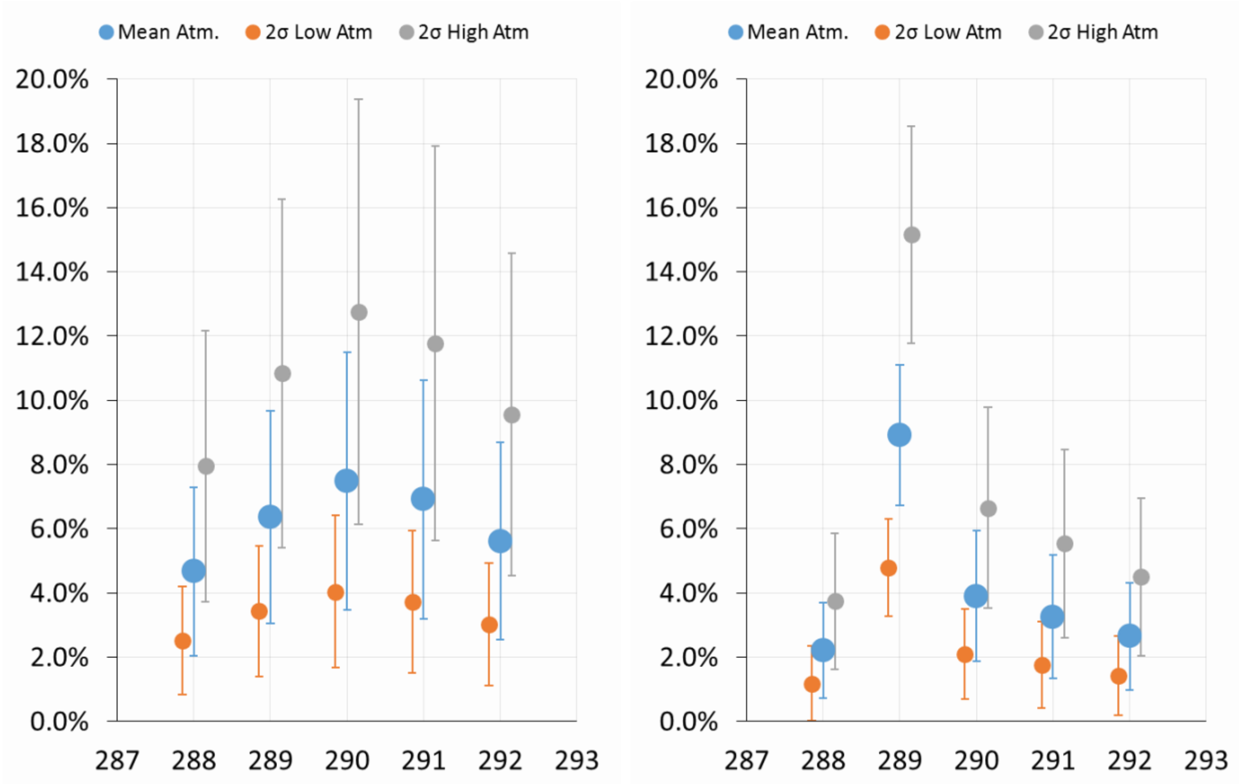


Figure 6: Predicted peak duty-cycles of the RCS thrusters during the final five proximal orbits for nominal (blue) and off-nominal atmospheres, high (gray) and low (orange). Y duty-cycle is on the left, Z is on the right.

Both plots in Figure 6 show that the predicted duty-cycles, even for a 2σ high atmosphere, are well below the RCS limit. As a point of reference, the T57 Titan flyby, the lowest in the Cassini Equinox Mission, had a peak duty-cycle of 69%. As another point of reference, the maximum predicted duty-cycle before the atmospheric contraction was 71%. Therefore, the capacity exists for the spacecraft to dip deeper into the atmosphere. The plots also show that Z-thruster duty-cycle is a slightly better indicator of atmospheric density than the Y-thruster duty-cycle, though they both suffer from the uncertainties in Table 2 making it difficult to distinguish between atmospheric densities.

The Y-thruster duty-cycles have significantly larger error bars due to the large uncertainty in the y-coordinate of the center of pressure [7]. Looking back at Table 2, the y-coordinate of the center of pressure has an uncertainty that is nearly an order of magnitude larger than the other two coordinates. The Z-thruster duty-cycles show less overlap between the nominal and 2σ-off-nominal atmospheres; however, Rev 289 is the only one with a distinct separation between them, a result of the planned attitude during that transit. Given these results, the spacecraft will not perform a pop-down maneuver until it has completed the Rev 289 transit, as that transit will give the best indication of the actual state of the atmosphere. In addition, collecting more data from subsequent transits before a pop-down serves to further reduce the uncertainty in the atmospheric state.

4. Pop-Down Maneuver Design

A pop-down maneuver performed near apoapsis will reduce both periapsis altitude and orbital period. Assuming the pop-down maneuver to be an instantaneous burn performed exactly at apoapsis, Figure 7 shows the change in periapsis and period resulting from a pop-down maneuver performed at the Rev 291 apoapsis.

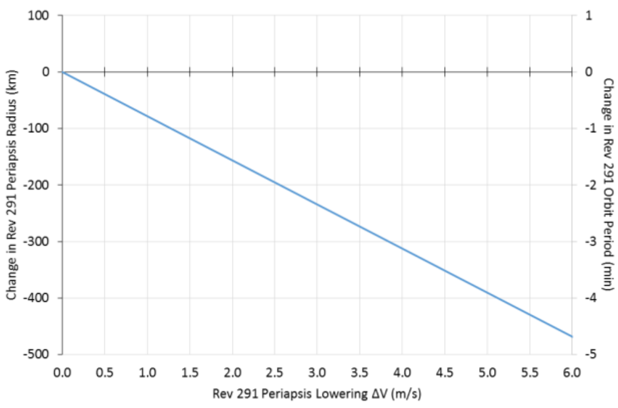


Figure 7: Effects of a pop-down maneuver on Rev 291 periapsis radius and orbit period.

Two constraints limit the magnitude of a pop-down maneuver: maximum burn time in a single nine-hour pass and maximum thruster duty-cycle of subsequent, post-pop-down, atmospheric transits. The former requires the burn to be no larger than 4 m/s if performed with the RCS thrusters; the latter can be inherited from that used for Titan flyby designs, which is 60%. In order to see how much a pop-down maneuver could change the predicted peak duty-cycle of a given transit, Rev 291 will again be used as an example. The ΔV required to achieve a given peak Y-thruster duty-cycle during the Rev 291 atmospheric transit is plotted in Figure 8. At 0.0 m/s (no pop-down maneuver), the three lines have the same duty-cycles as shown in the left plot of Figure 6, above. The duty-cycle values at 4.0 m/s give the maximum peak duty-cycle that could be achieved by performing a single pop-down maneuver with the RCS thrusters. For a nominal atmosphere, a single RCS maneuver could increase the peak duty-cycle from 7% to 50%. Increasing the duty-cycle to the 60% limit would require either another pop-down maneuver on RCS with an additional 0.3 m/s of ΔV, or using the main engine for the original pop-down in order to perform all 4.3 m/s in one burn.

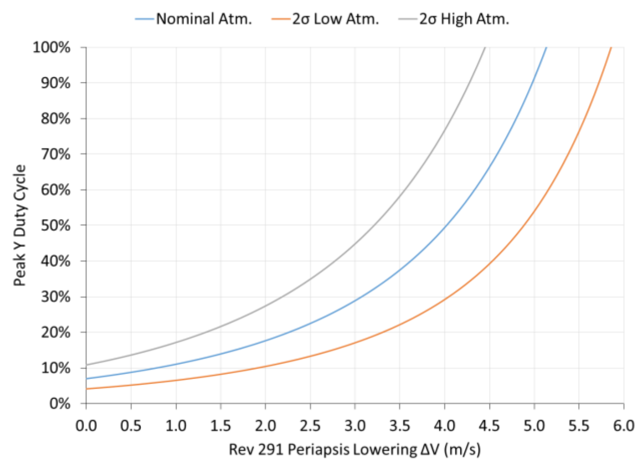


Figure 8: Peak Rev 291 Y-thruster duty-cycle vs. ΔV for a pop-down maneuver performed at the Rev 291 apoapsis. Each line represents a different atmospheric state: nominal (blue), 2σ-high off nominal (gray), and 2σ-low off nominal (orange).

Figure 8 also helps alleviate concerns about the duty-cycle detection method not providing enough resolution to design a safe pop-down maneuver, as a 4.0 m/s burn is not enough to take even a 2σ-high atmosphere case beyond an 80% peak duty-cycle. Moreover, the actual ΔV required to achieve the shown changes in duty-cycle will be larger due to the inefficiencies introduced when removing the assumption of an instantaneous burn right at apoapsis.

5. Downstream Trajectory Effects

The primary effect of a pop-down maneuver on the trajectory is the lowering of all subsequent periapsis altitudes. In addition, the earlier the spacecraft performs a pop-down maneuver and the larger it is, the greater its effects will be on the downstream trajectory, specifically on the timing of events. Of particular concern are the subsequent periapsis passes as these are the periods with the highest priority science observations and most sensitivity to timing errors. Figure 9 shows the effects of a single, max-duration, 4.0 m/s pop-down maneuver performed at the Rev 290 apoapsis on the position of the spacecraft. The maneuver lowers the points of minimum altitude above the tumble boundary by about 300 km for revs 290-292.

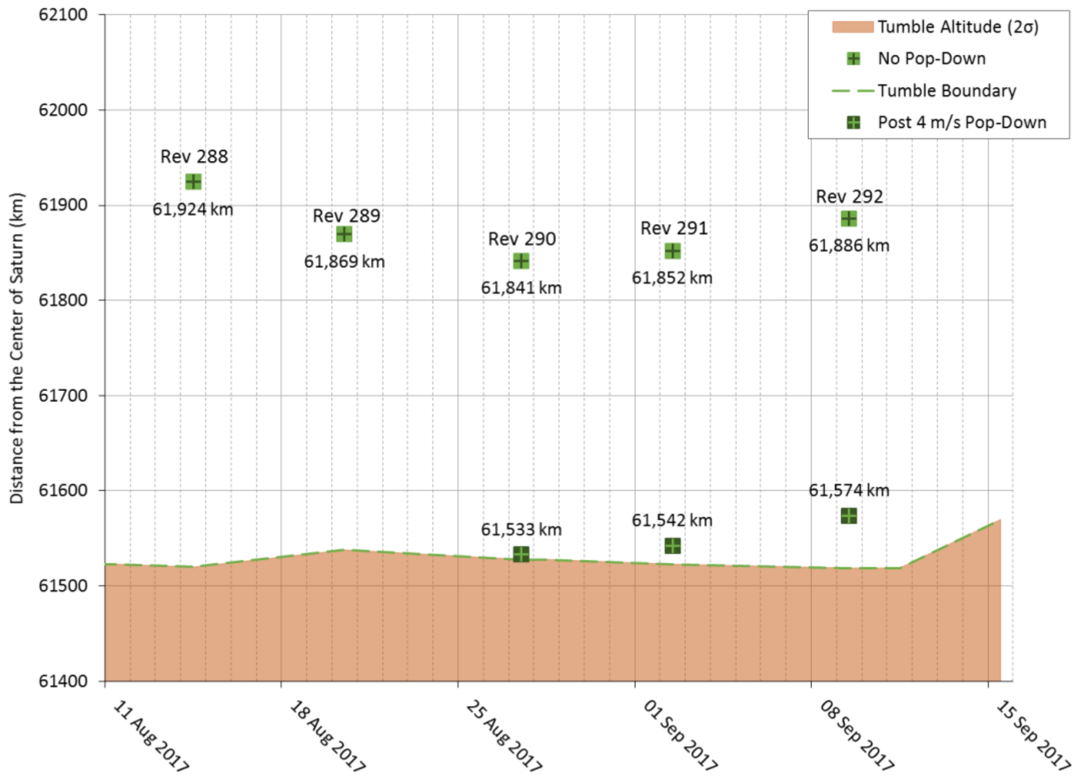


Figure 9: The points of minimum altitude above the tumble boundary for the nominal trajectory (light green) and for a trajectory with a 4 m/s pop-down maneuver at the Rev 290 apoapsis (dark green).

A pop-down maneuver not only reduces the periapsis radius of the trajectory but also the period of the orbits. The longer the spacecraft spends in a reduced-period orbit the more timing error accumulates with respect to the reference trajectory. Out at apoapsis, because the spacecraft is moving more slowly and targets of interest tend to be farther away, timing error tends to have less of an effect on observations. That said, the effect is likely not negligible and observations may be degraded. The periapsis designs are even more sensitive, which is why they have been padded with dead time on either side to allow them to be shifted in time to remove any error.

Table 3 shows the shift in event times associated with a pop-down maneuver of various magnitudes performed at the Rev 290 apoapsis.

Table 3: Timing shifts resulting from a pop-down maneuver at the Rev 290 apoapsis. Times shown are mm:ss, and negative times indicate the shift is earlier than the nominal timing.

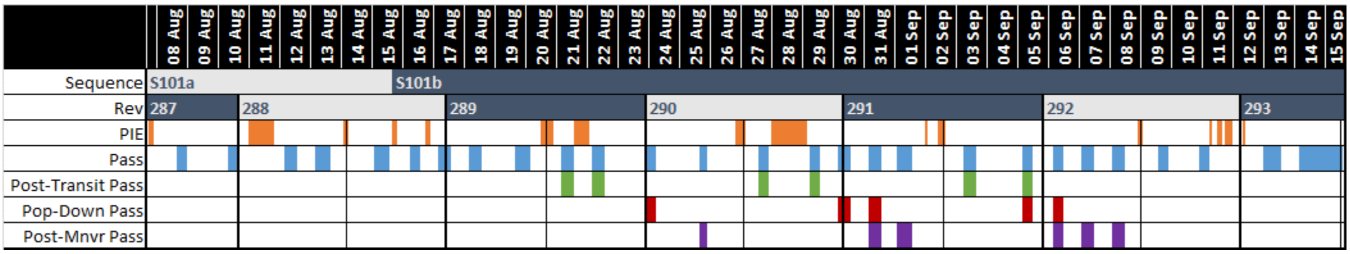
Rev		Nominal Timing	Rev 290 Pop-Down Maneuver Magnitude				
			0.5 m/s	1.0 m/s	2.0 m/s	3.0 m/s	4.0 m/s
290	Apoapsis	23 Aug 2017 20:56	-00:00	-00:00	-00:00	-00:00	-00:00
	Periapsis	27 Aug 2017 02:25	-00:12	-00:24	-00:49	-01:13	-01:37
291	Apoapsis	30 Aug 2017 07:54	-00:24	-00:49	-01:37	-02:26	-03:15
	Periapsis	02 Sep 2017 13:23	-00:37	-01:13	-02:26	-03:39	-04:52
292	Apoapsis	05 Sep 2017 18:54	-00:49	-01:37	-03:15	-04:52	-06:29
	Periapsis	09 Sep 2017 00:24	-01:01	-02:02	-04:03	-06:05	-08:07
293	Apoapsis	12 Sep 2017 05:44	-01:13	-02:25	-04:51	-07:18	-09:47
	Tumble	15 Sep 2017 10:52	-01:25	-02:50	-05:40	-08:31	-11:22

6. Reference Timeline

The timeline for this scenario is highly dependent on the DSN pass schedule. The first pass after each atmospheric transit determines the earliest the spacecraft can downlink the RCS thruster data. The time between the second pass after each transit and the pass nearest apoapsis determines how long the navigation team will have to design the maneuver. The time between the pop-down pass and the last pass before periapsis sets how long the navigation team will have to determine the new orbit such that the science planning and sequencing team can send the commands to shift the pointing design by the necessary amount of time.

Table 4 shows the planned DSN passes during the final five proximal orbits, in blue, along with the pre-integrated events (PIEs, which are high priority science observations), in orange. Additional rows have been added to distinguish certain types of passes: candidate pop-down maneuver passes (red), post-transit-pre-maneuver passes (green), and post-maneuver-pre-transit passes (purple).

Table 4: Schedule of all DSN passes and pre-integrated events in the final five proximal orbits.



The red passes are those nearest to apoapsis, and the best candidates for pop-down maneuvers. Ideally, each apoapsis would have two passes straddling it, one on either side. This would provide prime and backup opportunities for the OTM with minimal losses in burn efficiency due to the shift off apoapsis. This only occurs at Rev 292 opportunity. The Rev 291 opportunity has a prime window right at apoapsis and a backup over a day later, which would not result in too great a loss of efficiency. The Rev 290 opportunity has only one pass, with no good backup.

The green passes are those required for determining the post-transit orbit and designing the pop-down maneuver; the navigation team prefers at least two nine-hour passes but can make-do with one. The Rev 292 opportunity can provide two of these passes, but then there would be only one OTM pass for that opportunity.

The purple passes are those available for determining the new orbit and uplinking the associated timing shifts for subsequent periapsis pointing designs. Since the design value for the timing shift may be used, only one of these passes is required before the next periapsis. The Rev 291 opportunity is the only one that meets all the tracking requirements for a pop-down maneuver; however, Rev 292 opportunity can be done just without either a back-up window for the OTM or a second post-transit pass, which are acceptable given the optional nature of a pop-down.

In addition to meeting the tracking requirements, enough time must exist between the downlink of a transit's RCS thruster data and the prime maneuver window for:

- The AACS team to calculate the duty-cycle
- The Project to make a decision on whether or not to perform a pop-down
- Mission Planning and Project Science to convert duty-cycle to an appropriate navigation target altitude
- The navigation team to design the maneuver to the target altitude

From the last column in

Table 5, there are over eight days between the time the Rev 289 thruster data is returned and the prime opportunity for the Rev 291 pop-down maneuver. The minimum amount of time available for the above activities is 32 hours, which would only happen should the project decide to perform the pop-down at Rev 290. Even then, MP would have 16 hours to calculate a target altitude and Nav would have 16 to design the maneuver.

Table 5: Date and time of key events with the duration from their completion to the start of the next pop-down maneuver pass.

Rev	Event	Date (SCET)	Time to Next Pop-Down
288	Periapsis	14 Aug 2017 04:26	-9d 17h

	RCS Downlink Complete	15 Aug 2017 13:40	-8d 8h
289	Periapsis	20 Aug 2017 15:27	-3d 6h
	RCS Downlink Complete	21 Aug 2017 12:54	-2d 8h
	OD Tracking Complete	22 Aug 2017 12:34	-1d 9h
290	Apoapsis	23 Aug 2017 20:56	-0d 0h
	Prime Pop-down Pass Start	**23 Aug 2017 21:24**	**---**
	Periapsis	27 Aug 2017 02:25	-3d 1h
	RCS Downlink Complete	27 Aug 2017 21:54	-2d 5h
	OD Tracking Complete	29 Aug 2017 13:23	-0d 14h
	Prime Pop-down Pass Start	**30 Aug 2017 02:58**	**---**
291	Apoapsis	30 Aug 2017 07:54	-5d 19h
	Periapsis	02 Sep 2017 13:23	-2d 13h
	RCS Downlink Complete	03 Sep 2017 15:38	-1d 11h
	OD Tracking Complete	03 Sep 2017 15:38	-1d 11h
	Prime Pop-down Pass Start	**05 Sep 2017 02:37**	**---**
292	Apoapsis	05 Sep 2017 18:54	+0d 16h

As there are no PIEs in the apoapsis regions of these orbits, the project could change the tracking schedule should the navigation team deem the above times inadequate to safely design and execute a pop-down maneuver.

7. Risks and Mitigations

The main risks of this scenario are performing a pop-down maneuver that takes the spacecraft too deep into the atmosphere causing a loss of control authority and spacecraft safing and running out of bipropellant mid-maneuver.

The project maintains a contingency plan for handling bipropellant depletion during an OTM. This scenario would use that same plan, which would have the unfinished portion of the burn performed during the back-up opportunity using the RCS.

As for losing control authority, the larger the size of a pop-down and the earlier it takes place in the final five orbits, the more the likelihood of this risk increases as the spacecraft would be jumping deeper into the atmosphere with less information. There are three main mitigations to this: complete more transits before performing a maneuver, design the maneuvers to a peak duty-cycle of 60% for subsequent transits, and perform multiple maneuvers.

As was shown in Figure 6, using duty-cycle to detect atmospheric state can be a challenge given the uncertainties involved. However, the more transits completed, the more duty-cycle data points will be available to help reduce the uncertainties and hone in on the actual state of the atmosphere. While Figure 6 shows that waiting for the Rev 289 transit data is practically a necessity, it also shows that waiting for subsequent transits has diminishing returns. The baseline is to wait until after the Rev 290 transit before performing a pop-down.

Limiting the magnitude of the pop-down maneuver such that the increase in the peak duty-cycles of subsequent transit is well below 100% further mitigates the risk of going too deep. Using the state of the atmosphere determined by the transit duty-cycles, the mission planning team would calculate a target altitude that would yield a peak duty-cycle of 60% during the remaining transits. This would leave 40% margin for other torques, the uncertainties in the atmosphere, and the uncertainties listed in Table 2.

Performing multiple pop-down maneuvers not only has the benefit of allowing for the collection of more transit data between the maneuvers, but also, the additional transit data would be from deeper in the atmosphere. As can be seen in Figure 10, lowering altitude increases the separation in duty-cycle values created by the off-nominal atmospheres. This means both the quantity and quality of the transit data would increase. Multiple maneuvers also allow the spacecraft to perform more than 4 m/s of total ΔV if using the RCS, increasing the range of reachable altitudes and further improving science value.

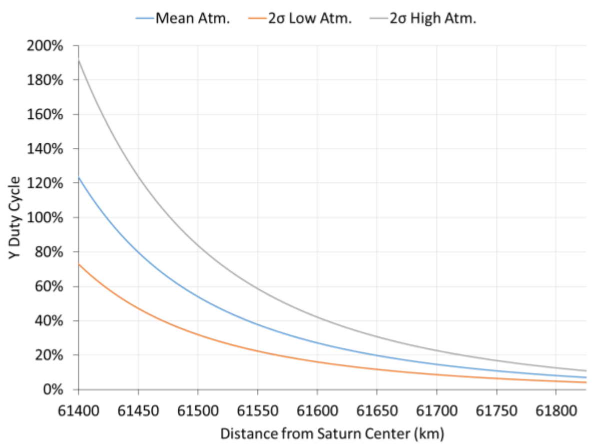


Figure 10: RCS Y-thruster peak duty-cycle versus radial distance from Saturn's center.

Given the minimal impact of bipropellant depletion during a pop-down and the ability to design it with plenty of duty-cycle margin, the project is considering this scenario a viable option for execution during the final five orbits. Ultimately though, the decision of whether or not to perform the pop-down will fall to the Cassini project manager.

8. CONCLUSION

Given the current thermosphere model, mission planning predicts that the maximum RCS thruster duty-cycle during the final five proximal orbits will be less than 13% (2σ). This compares to the previous value of 71%, shifting the concern from spacecraft health-and-safety to science value. To that end, this paper explored a "make-better" science scenario for modifying the Cassini spacecraft's trajectory to dip deeper into Saturn's atmosphere during the final five proximal orbits by performing one or more pop-down maneuvers near the orbits' apoapses.

The catch comes in accurately determining the state of the atmosphere in order to design a pop-down maneuver. Using RCS thruster duty-cycles as a proxy for atmospheric state is a viable method, though not without its shortcomings. Multiple data points should be obtained from atmospheric transits before executing a pop-down in order to reduce uncertainties. In addition, designing the maneuver to a 60% predicted peak duty-cycle would ensure adequate margin for absorbing errors in the estimate of atmospheric state.

The current DSN passes provide two opportunity for a pop-down maneuver that meet all tracking requirements, near the apoapses of revs 291 and 292.

The priority placed on obtaining high-quality, in-situ atmospheric measurements combined with the fact that Titan flybys have been designed to 60% duty-cycles suggests that lowering periapsis passages during the final five orbits is a viable option that the project will consider during flight.

ACKNOWLEDGMENTS

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

[1] E. J. Sturm, "Contingency Planning for Cassini's Final Mission Phase," in *IEEE Aerospace Conference Proceedings*, Big Sky, 2016.

[2] T. Koskinen, B. Sandel, R. Yelle, D. Strobel, I. Muller-Wodarg and J. Erwin, "Saturn's variable thermosphere from Cassini/UVIS occultations," *Icarus*, vol. 260, pp. 174-189, 2015.

[3] M. E. Bittner, W. Heventhal, E. J. Sturm and J. Webster, "The Last Orbit: Planning Cassini's Plummet into Saturn," in *SpaceOps Conference Proceedings*, Daejeon, 2016.

[4] T. J. Barber and R. T. Cowley, "Initial Cassini Propulsion System In-Flight Characterization," in *38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Indianapolis, 2002.

[5] E. J. Sturm, T. J. Barber and D. Roth, "Ensuring Cassini's End-of-Mission Propellant margins," in *IEEE Aerospace Conference Proceedings*, Big Sky, 2015.

[6] T. A. Burk, "Cassini Orbit Trim Maneuvers at Saturn – Overview of Attitude Control Flight Operations," in *AIAA Guidance, Navigation, and Control Conference*, Portland, 2011.

[7] L. G. Andrade, T. A. Burk and F. Pelletier, "Titan Density Reconstruction Using Radiometric and Cassini Attitude Control Flight Data," in *AIAA Guidance, Navigation, and Control Conference Proceedings*, Kissimmee, 2015.

BIOGRAPHY

Erick Sturm *is the current Mission Planning lead for the Cassini Mission. Prior to joining Cassini, he served as a mission engineer and mission architect for the Mars Advanced Formulation Office and for various planetary mission concepts. He joined JPL in 2005 fresh out of California Polytechnic State University, San Luis Obispo, where he received his B.S. in Aerospace Engineering, B.A. in Physics, and M.S. in Aerospace Engineering.*